

Soil-profile distribution of inorganic N during 6 years of integrated crop-livestock management



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ABSTRACT

Excessive accumulation of soil nitrate-N can threaten water and air quality. How integrated crop-livestock systems might influence soil-profile nitrate-N accumulation has not been investigated. Therefore, we determined soil nitrate-N accumulation during 6 years of evaluation of diverse cropping systems on a Typic Kanhapludult in Georgia, USA. Of the total change in soil nitrate-N content that occurred during 6 years (i.e. increase of $14 \text{ kg N ha}^{-1} \text{ year}^{-1}$), an average of 60% occurred in the primary rooting zone (0–90-cm depth) and 40% occurred in the zone below typical rooting (90–150-cm depth). Soil nitrate-N accumulation was greater in cropping systems with greater N fertilizer input, while it was surprisingly insensitive to differences in harvested N output. Soil nitrate-N accumulation was greater under conventional tillage than under no tillage at all soil depths (e.g. $5.1 \pm 4.2 \text{ kg N ha}^{-1} \text{ year}^{-1}$ greater at a depth of 90–150 cm), suggesting soil disturbance was a key factor in mobilizing N and keeping it more disassociated from the organic–inorganic cycling system. Grazing of cover crops had variable effects on soil nitrate-N content: greater soil nitrate-N content in the rooting zone at the end of 1 year ($63 \text{ vs. } 47 \text{ kg N ha}^{-1}$), greater soil nitrate-N content in the zone below typical rooting at the end of 3 and 4 years ($91 \text{ vs. } 70 \text{ kg N ha}^{-1}$), and lower soil nitrate-N content in the rooting zone at the end of 6 years ($89 \text{ vs. } 120 \text{ kg N ha}^{-1}$). These results confirm the beneficial effect of no-tillage management on moderating nitrate-N accumulation in the soil profile and indicate a variable, but mostly neutral effect of cover crop grazing on soil nitrate-N accumulation.

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1. Introduction

Efficient utilization of N in agricultural systems is a continuous goal to meet high production demands and preserve environmental quality. Soil organic matter can supply a portion of N to agronomic systems through steady-state mineralization from soil microbial activity. However, the demand for N in modern cropping systems is often far in excess of what soil organic matter can supply. Application of inorganic N to cereal cropping systems is often needed to stimulate rapid growth at critical times of plant development to achieve yield potential. Unfortunately, excessive N is often a consequence in high-production environments, resulting in threats to surface and ground water quality, as well as contributing to greenhouse gas emissions and ozone-depleting aerosols (Hatfield and Follett, 2008).

High N demand by cereal grain crops and subsequent removal of N in harvested grain are key reasons for continuous inputs of N fertilizer to agroecosystems. Comparison of cropping systems with

low and high N harvest in grain given equal N inputs and differences in N uptake due to soil fertility restrictions in Punjab India, resulted in an inverse relationship between nitrate-N accumulation in the soil profile and N removed by harvest (Benbi et al., 1991). In long-term continuous fertility experiments in Oklahoma, wheat (*Triticum aestivum* L.) grain yield was maximized with application of $53 \pm 8 \text{ kg N ha}^{-1} \text{ year}^{-1}$, while the point at which soil-profile nitrate-N started to accumulate was $94 \pm 15 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (Raun and Johnson, 1995). These data indicate a relatively narrow window of opportunity to limit excess nitrate-N accumulation in the soil profile.

Soil tillage could be expected to alter soil N dynamics and potential movement of nitrate-N through the soil profile due to disturbance that could sever pore networks and enhance soil biological activity. Soil-profile nitrate-N content under no tillage (NT) was $67 \pm 14\%$ of that under conventional tillage (CT) during the second year of a corn (*Zea mays* L.) production study with a diversity of cover crops and fertilizer rates in Pennsylvania (Dou et al., 1995). During yearly measurements of a 3-year study in Nebraska, nitrate-N content was nearly equal ($5 \pm 26 \text{ kg N ha}^{-1}$ lower) under NT as under CT in the surface 0–90-cm depth, but was lower ($23 \pm 21 \text{ kg N ha}^{-1}$) under NT than under CT in the 90–150-cm depth (Kessavalou and Walters, 1999). In Iowa, soil-profile nitrate-N content tended to be

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lower under NT than under CT, but leachate concentration of inorganic N at 120-cm depth was unaffected by tillage system (Al-Kaisi and Licht, 2004). During a 3-year study on a Typic Dystrochrept in Maryland, soil-profile nitrate-N concentration was significantly lower under NT than under CT, especially when N fertilizer rates exceeded levels needed to optimize yield, but also at lower rates (Angle et al., 1993). Reasons for this difference were outlined as presence of a cover crop in the NT system that could have removed soil nitrate, greater grain yield under NT than under CT that would have removed N from the agroecosystem, and potentially greater ammonia volatilization and denitrification from surface-applied N fertilizer with NT. In an 11-year evaluation in Minnesota, soil water drainage to tiles was greater under NT than under CT (315 vs. 280 mm, respectively), but total nitrate-N loss was 5% lower under NT than under CT due to reduced concentration of nitrate-N in the soil profile under NT (Randall and Iragavarapu, 1995).

Type of cropping system can have a dramatic effect on soil nitrate-N accumulation in the soil profile. In Connecticut, soil nitrate-N was reduced with perennial grass/forage-legume systems and double-crop systems compared with a corn-only system (Guillard et al., 1995). Likewise in Saskatchewan Canada, cropping systems with low diversity and high fertilizer inputs resulted in greater soil nitrate-N accumulation than cropping systems with high diversity and reduced or organic fertilizer inputs (Malhi et al., 2002).

Integrated crop-livestock systems that utilize grazing cattle (*Bos taurus*) to harvest forages in rotation with grain crops on the same land may have some advantages in utilizing N more efficiently than simple crop systems with the same crop growth pattern occurring each year. Unfertilized grain crops in rotation with forage legumes can be high yielding, while sparing the need for inorganic N inputs (Franzluebbers and Francis, 1995; Hoepfner et al., 2006). In addition, cover crops do not necessarily require high N inputs for success, and therefore, diverse cropping systems can be developed to reduce the intensity of inorganic N inputs to the agro-ecosystem. Scavenging of residual soil nitrate by winter cereal crops has been observed in many studies and locations (Dabney et al., 2001; Delgado et al., 2007), suggesting the potential for excessive inorganic N to become remobilized into the plant-topsoil organic cycling domain to prevent leaching below the effective rooting zone. In Denmark, leachate accumulation at 100-cm depth was $57 \pm 25 \text{ kg N ha}^{-1} \text{ year}^{-1}$ when soil was left fallow over winter and $37 \pm 23 \text{ kg N ha}^{-1} \text{ year}^{-1}$ when perennial ryegrass (*Lolium perenne* L.) was grown as a catch crop (Møller Hansen and Djurhuus, 1997).

Cattle grazing cover crops can stimulate soil biological activity and alter N mineralization-immobilization dynamics (Franzluebbers and Stuedemann, 2007), but how such integration might influence the leaching potential of inorganic N has not been investigated. Therefore, we analyzed soil profiles during the course of 6 years in an integrated crop-livestock experiment to determine the impact of cover crop management on residual soil nitrate-N concentration in the rooting zone (0–90 cm) and the zone below typical rooting (90–150 cm). We hypothesized that cattle grazing of cover crops would stimulate N release from organically bound plant biomass and soil organic matter and lead to greater accumulation of nitrate-N in the soil profile. We questioned whether such accumulation might be restricted to the rooting zone where plants could utilize the nutrients or leach beyond the rooting zone.

2. Materials and methods

2.1. Site characteristics and management

The experiment was located near Watkinsville, GA, USA (33°62' N, 83°25' W) on Cecil sandy loam and sandy clay loam soils (fine,

kaolinitic, thermic Typic Kanhapludults) with 2–6% slope. Soil was moderate to strongly acidic (pH 5–6). Long-term mean annual temperature is 16.5 °C, precipitation is 1250 mm, and pan evaporation is 1560 mm. Excess precipitation in winter and deficit precipitation in summer are typical for the location.

Beginning in 1982, a total of 18 paddocks (0.7-ha each) were managed as tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire] pastures, varying in tall fescue-endophyte association and fertilization level (Belesky et al., 1988). Pastures were grazed with Angus cattle each year, primarily in spring and autumn. All fertilization was suspended after 1997 to help avoid further accumulation of inorganic N in the soil profile below 30 cm (Franzluebbers et al., 2000). Sixteen of the 18 pastures were terminated either with moldboard plow (CT) or glyphosate (NT) in May 2002, at which time a new experimental design was imposed onto this previous design by allocating four primary treatments in a stratified, but randomized manner to account for previous management.

The experimental design from 2002 to 2005 consisted of a factorial arrangement of (1) tillage (CT and NT) and (2) cropping system (summer grain/winter cover crop and winter grain/summer cover crop) with four replicated paddocks each, for a total of 16 main plots. Two of the original 18 pastures remained as control pastures. Main plots were split into grazed (0.5 ha) and ungrazed (0.2 ha) cover crop treatments.

Tillage systems were: (1) conventional disk tillage (CT) following harvest of each grain and cover crop and (2) no tillage (NT) with glyphosate to control weeds prior to planting. Tillage treatments were initiated in May 2002. Initial CT treatment consisted of moldboard plowing to a depth of 25–30 cm. Disk plowing only to a depth of 15–20 cm occurred in subsequent years two to several times between crops, depending on amount of residue present. Pasture was terminated in the NT treatment with two applications of glyphosate [isopropyl amine salt of N-(phosphonomethyl) glycine, 2.9 kg a.i. ha⁻¹ in May and 1.2 kg a.i. ha⁻¹ in June 2002]. Thereafter, glyphosate was applied typically in one pre- or immediately after-planting application (0.8–1.7 kg a.i. ha⁻¹) and sometimes a few weeks after emergence when using glyphosate-tolerant crops.

Cropping systems were intentionally diverse to produce both summer and winter crops each year. Crop rotation changed in 2005 (Table 1), but tillage system and cover crop management remained consistent during the period of investigation. Grain crops of sorghum [*Sorghum bicolor* (L.) Moench] and soybean [*Glycine max* (L.) Merr.] were typically planted in June and harvested in October, corn was planted in April and harvested in September, and wheat was planted in November and harvested in June. Cover crops of cereal rye (*Secale cereale* L.), wheat, annual ryegrass (*Lolium multiflorum* Lam.), and crimson clover (*Trifolium incarnatum* L.) were typically planted in November and terminated in May and pearl millet [*Pennisetum glaucum* (L.) R.Br.] was planted in June/July and terminated in September/October.

Cover crop management was: (1) no grazing and allowing plants to reach early flowering prior to termination and (2) grazing with cattle to consume ~90% of available forage during 4–10 week periods once forage reached ~30 cm tall, irrespective of weather conditions. Cattle stocking rate was managed with a put-and-take approach to equalize available forage among treatments within a grazing period. Cover crops were stocked with yearling Angus steers in the summer of 2002 and in the spring of 2003. Thereafter, cow/calf pairs were used to simulate a more typical approach in the region. Ungrazed cover crops were grown until ~2 weeks prior to planting of the next crop and either (1) mowed prior to CT operations (disk) as green manure or (2) mechanically rolled to the ground in the NT system to provide surface mulch.

Application of N was moderate during the first 3 years ($96 \pm 7 \text{ kg N ha}^{-1} \text{ year}^{-1}$), but was adequate to assure early plant

Table 1

Precipitation and N inputs/outputs of four cropping systems and two tillage regimes (CT=conventional tillage and NT=no tillage) during 6 years of evaluation.

Year/season	Main crop sequence	Alternative crop	Precipitation (mm) ^a	N applied (kg ha ⁻¹)		N harvested (kg ha ⁻¹)	
				Main	Alternative	CT	NT
Summer grain/winter cover							
2002 Summer	Sorghum		401	50		24	14
2002 Winter	Rye		615	52		^b (2)	^b (3)
2003 Summer	Sorghum		817	51		71	76
2003 Winter	Rye		462	40		^b (3)	^b (6)
2004 Summer	Sorghum		728	48		9	16
2004 Winter	Rye		916	50		^b (1)	^b (2)
2005 Summer	Corn		622	163		104	115
2005 Winter	Clover + rye	Ryegrass + rye	715	0	45	^b (1)	^b (1)
2006 Summer	Soybean		387	0		132	211
2006 Winter	Clover + rye	Ryegrass + rye	591	0	51	^b (1)	^b (2)
2007 Summer	Corn		230	105		7	42
2007 Winter	Wheat		593	47		76	69
Mean/year			1180	101	117	71 (72)	91 (93)
Winter grain/summer cover							
2002 Summer	Pearl millet		401	50		^b (5)	^b (5)
2002 Winter	Wheat		615	52		48	49
2003 Summer	Pearl millet		817	45		^b (3)	^b (3)
2003 Winter	Wheat		462	40		51	42
2004 Summer	Pearl millet		728	50		^b (1)	^b (2)
2004 Winter	Wheat		916	50		48	50
2005 Summer	Pearl millet		622	56		^b (3)	^b (3)
2005 Winter	Clover + rye	Ryegrass + rye	715	0	45	^b (1)	^b (1)
2006 Summer	Corn		387	97		21	33
2006 Winter	Wheat		591	51		65	25
2007 Summer	Soybean		230	0		57	89
2007 Winter	Clover + rye	Ryegrass + rye	593	0	47	^b (3)	^b (2)
Mean/year			1180	82	97	48 (51)	48 (51)

Note: Soil samples were collected between crops indicated by double lines.

^a Summer precipitation considered May through September; Winter precipitation considered October through April.^b Small amount of N removed in animal gain (value in parentheses) when cover crop grazed, otherwise ungrazed.

growth and development with further growth dependent upon the mineralization of stored nutrients in soil organic matter. Nitrogen rate was similar in subsequent years, but greater for corn (160 kg N ha⁻¹) and zero for soybean and clover. Extractable P and K concentrations in the surface 7.5 cm of soil following pasture were >100 mg P kg⁻¹ soil and 400 mg K kg⁻¹ soil, levels considered adequate for crop production. Plant and animal production were reported in Franzluebbbers and Stuedemann (2007, 2013a), soil-surface responses during early years were reported in Franzluebbbers and Stuedemann (2008a,b), and deep-profile soil C and N were reported in Franzluebbbers and Stuedemann (2013b).

2.2. Soil sampling and analyses

Soil was collected at the end of ~1 year of management in February 2003, at the end of ~2 years of management in October 2003, at the end of ~3 years of management in October 2004, at the end of ~4 years of management in October 2005, and at the end of ~6 years of management in December 2007. An hydraulic probe (4-cm inside diameter) mounted on a tractor was pushed into the soil to a depth of 150 cm. Multiple cores were sectioned into depth increments of 0–20, 20–40, 40–60, 60–90, 90–120, and 120–150 cm and pooled (2 cores per ungrazed and 4 cores per grazed experimental unit). Differences in number of cores reflected differences in plot size. Cattle camping zones near permanent shade and water sources on one side of plots was avoided. Surface residue was pushed to the side prior to sampling. Soil was dried at 55 °C for ≥3 d. Bulk density was calculated from the total dry weight of soil and volume of coring device in December 2007 only. Prior to laboratory analyses, soil was sieved coarsely (8 mm openings) and then a representative portion ground ≤2 mm.

Inorganic N (NH₄-N and NO₃-N + NO₂-N) from the first 4 years was determined from a filtered extract of a 10-g subsample of

soil shaken with 20 mL of 2 M KCl for 30 min by salicylate-nitroprusside (NH₄-N) and Cd-reduction autoanalyzer techniques (Mulvaney, 1996). Samples collected in December 2007 were processed later using the same extraction technique, but analyzed with salicylate-nitroprusside and hydrazine techniques (Kempers and Luft, 1988). Samples in December 2007 appeared to have gained significant NH₄-N during storage prior to analysis, and therefore, results of NH₄-N were not included in the analyses here.

2.3. Statistical analyses

With the change in crop rotation in 2005, a total of 16 treatments (4 cropping systems × 2 tillage regimes × 2 cover crop management) with 2 replications was the result. We analyzed these 16 treatments with limited replication to detect whether crop type and timing were important in soil-profile N accumulation. Main plots were tillage and cropping system and split-plots were cover crop management. Inorganic N concentration within a depth increment was analyzed for variance due to tillage, cropping system, and cover crop management using SAS v. 9.3. Error terms were block × tillage × cropping system to test for main-plot effects and block × tillage × cropping system × cover crop management to test for split-plot effects. Linear regression with an intercept common to all treatments within a depth was used to test the significance of temporal changes among treatments. Areal estimates of soil-profile nitrate-N were calculated by accounting for differences in bulk density and depth. Mean soil bulk density by depth increment was used for all observations (i.e. 1.23 Mg m⁻³ at 0–20 cm, 1.43 Mg m⁻³ at 20–40 cm, 1.45 Mg m⁻³ at 40–60 cm, 1.46 Mg m⁻³ at 60–90 cm, and 1.47 Mg m⁻³ at 90–120 and 120–150 cm). The soil profile was divided into three sections representing the upper rooting zone (0–40 cm), the lower rooting

zone (40–90 cm), and the zone generally below roots (90–150 cm). Effects were considered significant at $P \leq 0.10$.

3. Results and discussion

Soil nitrate-N concentration was highly variable in this experiment, more so within depth increments as a function of treatment and year of sampling than across depths (Fig. 1). Distribution of data was concentrated (i.e. 25–75% quartile range) from 4–9 mg kg⁻¹ at 0–20 cm, 4–7 mg kg⁻¹ at 20–40 cm, 4–8 mg kg⁻¹ at 40–60 cm, 3–6 mg kg⁻¹ at 60–90 cm, 3–9 mg kg⁻¹ at 90–120 cm, and 4–13 mg kg⁻¹ at 120–150 cm. Mean value became larger at a depth of 120–150 cm (generally considered beyond the typical crop rooting zone). In contrast, soil ammonium-N concentration varied more as a function of depth than due to treatment and year of sampling. The interquartile range for ammonium-N was 6–8 mg kg⁻¹ at 0–20 cm, 4–5 mg kg⁻¹ at 20–40 cm, 2–3 mg kg⁻¹ at 40–60 and 60–90 cm, and 1–2 mg kg⁻¹ at 90–120 and 120–150 cm. The logarithmic decline in ammonium-N concentration with depth was also observed under perennial pasture soil at a nearby site (Franzluebbers and Stuedemann, 2003). However, the depth distribution of nitrate-N in this study was more uniform and greater in concentration than in the perennial pasture experiment at a nearby site. Compared to the soil-profile inorganic N content in this same experiment 5 years prior to the initiation of this integrated crop-livestock study, soil inorganic N was more uniformly distributed and lower in content

due to termination of N fertilizer application during the last 5 years of the pasture (Franzluebbers et al., 2000).

Soil nitrate-N content following termination of previous perennial pasture was little affected by tillage and cover crop management during the first year (Table 2). A minor, but consistent effect of greater nitrate-N content under grazed than ungrazed cover crop management was observed in the lower rooting zone (40–90-cm depth). This effect was not present above and below this depth. At the end of 2 years of management, this effect dissipated to a non-significant numerical comparison that was consistent. At the end of 2 years, the upper rooting zone (0–40-cm depth) had greater soil nitrate-N content under NT than under CT. No other differences in soil nitrate-N content occurred at this sampling date.

At the end of 3 years of management, soil nitrate-N content in the lower rooting zone was lower under NT than under CT (Table 2). This effect was consistent with greater nitrate-N content in the zone below typical rooting (90–150-cm depth). The combination of these two consistent effects led to lower nitrate-N content under NT than under CT within the entire 0–150-cm profile. Another highly significant effect at this sampling was for greater nitrate-N content under grazed than ungrazed cover crop management in the zone below typical rooting. Combined with consistent numerical comparisons in the upper and lower rooting zones, the entire 0–150-cm profile had greater nitrate-N content under grazed than ungrazed cover crop management. Enhanced mineralization of nutrients contained in cover crop biomass through animal consumption and deposition of N-enriched urine from grazing cattle may have led to these results, suggesting greater leaching below the rooting zone.

At the end of 4 years of management, soil nitrate-N content was no longer statistically lower under NT than under CT within individual depth sections, but the numerical comparison remained consistent (Table 2). When calculated to the entire 0–150-cm profile, soil nitrate-N content was statistically lower under NT than under CT, similar to the effect at the end of 3 years of management. Also consistent with the results at the end of 3 years, nitrate-N content was greater under grazed than ungrazed cover crop in the zone below typical rooting and in the entire 0–150-cm profile. The consistency of results between years of sampling gives confidence that the effects were real and not spurious.

At the end of 6 years of management, both tillage and cover crop management effects were significant at most depths (Table 2). The tillage effect was similar to the two previous samplings, but the cover crop effect was in contrast to previous results. Soil nitrate-N content was lower under grazed than ungrazed cover crop management in both the upper and lower rooting zones, was not different between treatments in the zone below typical rooting, and was lower under grazed than ungrazed condition in the entire 0–150-cm profile. Of the 28 kg N ha⁻¹ difference between grazed and ungrazed condition in the entire profile, 75% was due to the difference in the upper rooting zone. These data indicate differences in timing of N mineralization from manure transformed cover crop biomass compared with plant-litter accumulated surface residue, since soil organic matter fractions did not differ between the two cover crop management systems, at least during the first 3 years of management (Franzluebbers and Stuedemann, 2008a). Whatever the cause, the effect was clearly being limited to the typical crop rooting zone and primarily in the upper rooting zone.

A large and complicated set of biological and environmental factors controls inorganic N dynamics in the soil profile. Although inorganic N changes are likely to occur on a monthly basis due to temperature and moisture fluctuations, as well as plant N uptake dynamics based on extent and distribution of roots, our study provided a coarser level of evaluation of the multi-year changes

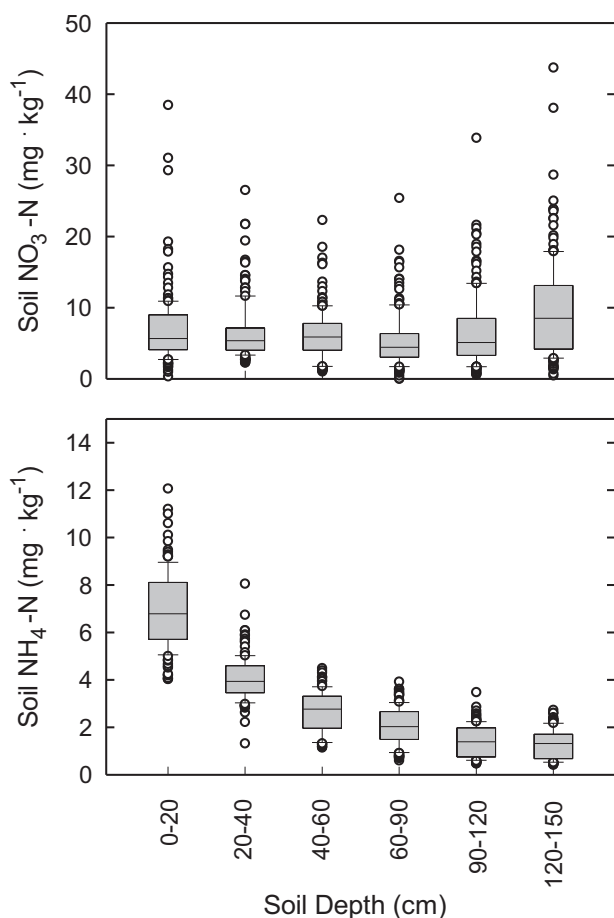


Fig. 1. Soil nitrate (NO₃)-N and ammonium (NH₄)-N concentration as affected by depth of sampling. Data represent all observations independent of treatment and year of sampling. Range from bottom to top of box contains 25–75% of all values, while the central bar represents the median and whisker bars represent 1.5 times the interquartile range.

Table 2

Soil nitrate ($\text{NO}_3\text{-N}$) as affected by tillage (CT, conventional tillage and NT, no tillage), cover crop management (ungrazed and grazed), and soil-profile zone (0–40 cm is the upper rooting zone, 40–90 cm is the lower rooting zone, and 90–150 cm is below the typical rooting zone) at the end of 1, 2, 3, 4, and 6 years of evaluation.

Tillage	Cover crop management	Soil NO ₃ -N (kg ha ⁻¹)				
		0–40 cm	40–90 cm	0–90 cm	90–150 cm	0–150 cm
February 2003 (end of 1 year)						
CT	Grazed	26	72	98	46	144
CT	Ungrazed	22	52	74	66	141
NT	Grazed	23	53	77	31	108
NT	Ungrazed	24	41	65	65	130
Source of variation	df					
Tillage	1, 7	0.90	0.13	0.26	0.80	0.55
Cover crop	1, 14	0.34	0.06	0.05	0.29	0.75
Tillage × cover	1, 14	0.33	0.63	0.49	0.78	0.66
October 2003 (end of 2 years)						
CT	Grazed	23	17	41	74	114
CT	Ungrazed	22	12	34	58	92
NT	Grazed	35	16	51	56	107
NT	Ungrazed	28	15	43	65	108
Source of variation	df					
Tillage	1, 7	0.08	0.71	0.11	0.78	0.85
Cover crop	1, 14	0.21	0.17	0.14	0.85	0.59
Tillage × cover	1, 14	0.45	0.36	0.91	0.48	0.55
October 2004 (end of 3 years)						
CT	Grazed	33	45	78	98	176
CT	Ungrazed	26	44	70	77	147
NT	Grazed	31	38	69	83	153
NT	Ungrazed	30	32	62	58	120
Source of variation	df					
Tillage	1, 7	0.30	0.10	0.16	0.10	0.06
Cover crop	1, 14	0.11	0.37	0.13	0.008	0.009
Tillage × cover	1, 14	0.24	0.55	0.89	0.76	0.88
October 2005 (end of 4 years)						
CT	Grazed	39	57	96	109	206
CT	Ungrazed	40	60	100	85	185
NT	Grazed	44	39	83	74	157
NT	Ungrazed	38	44	82	58	140
Source of variation	df					
Tillage	1, 7	0.54	0.12	0.18	0.11	0.10
Cover crop	1, 14	0.34	0.21	0.77	0.001	0.002
Tillage × cover	1, 14	0.17	0.69	0.57	0.41	0.75
December 2007 (end of 6 years)						
CT	Grazed	61	49	111	96	206
CT	Ungrazed	82	58	141	93	234
NT	Grazed	31	37	67	69	137
NT	Ungrazed	53	45	98	68	166
Source of variation	df					
Tillage	1, 7	<0.001	0.14	0.001	0.11	0.002
Cover crop	1, 14	0.06	0.08	0.02	0.78	0.10
Tillage × cover	1, 14	0.95	0.91	0.99	0.90	0.95

that can be expected in diverse cropping systems. Precipitation is a key controlling factor for determining mineralization of organic residues and flushing nutrients vertically through the soil profile. Precipitation varied considerably during this 6-year period from ~64% of normal precipitation during the first year to 123% of normal precipitation during the fourth year. Year 2 received 115% of normal, year 3 received 95% of normal, and years 5–6 received 77% of normal precipitation (Table 1). The balance between N inputs and N outputs is another important variable controlling inorganic N distribution in soil. In general, N inputs exceeded N outputs (i.e. harvested grain) during most years (~40 kg ha^{-1} in years 1 and 2, ~60 kg ha^{-1} in year 3, ~80 kg ha^{-1} in year 4, and ~10 kg ha^{-1} deficit in years 5–6). We also expected tillage system (disturbed by disk tillage or not with no tillage) and cover crop management (plant residues left intact when ungrazed or undergoing physical and biochemical transformations when

grazed by cattle) to exert multi-year influences on inorganic N in the soil profile.

Soil nitrate-N content generally increased with time (Table 3). The rate of increase across treatments was 6.8 $\text{kg N ha}^{-1} \text{ year}^{-1}$ ($P < 0.001$) in the upper rooting zone, 1.8 $\text{kg N ha}^{-1} \text{ year}^{-1}$ ($P = 0.12$) in the lower rooting zone, and 5.8 $\text{kg N ha}^{-1} \text{ year}^{-1}$ ($P = 0.008$) below the typical rooting zone. Assuming that nitrate-N is lost to groundwater leaching when it reaches a depth of 90–150 cm, these data indicate significant leaching loss of N in this environment. Some loss of N is certainly expected in an environment that receives an average of 100 mm month^{-1} and occasionally 200 mm month^{-1} during wet periods. Nitrate-N content in this study was $149 \pm 69 \text{ kg N ha}^{-1}$ within the 0–150-cm profile across all sampling dates and treatments. This compares with $78 \pm 67 \text{ kg N ha}^{-1}$ within the 0–120-cm profile of a Typic Hapludult in Pennsylvania (Dou et al., 1995), $143 \pm 51 \text{ kg N ha}^{-1}$

Table 3

Regression of soil nitrate (NO_3)-N content with time as a function of cropping system (summer grain/winter cover with low and high N and winter grain/summer cover with low and high N), tillage (conventional tillage and no tillage), cover crop management (ungrazed and grazed), and depth of sampling (0–40 cm is the upper rooting zone, 40–90 cm is the lower rooting zone, and 90–150 cm is below the typical rooting zone).

Comparison	Soil depth (cm)				
	0–40	40–90	0–90	90–150	0–150
<i>Intercept (kg N ha^{-1})</i>					
Common to all	14 ± 3	36 ± 4	49 ± 6	53 ± 8	102 ± 11
<i>Slope ($\text{kg N ha}^{-1} \text{ year}^{-1}$)</i>					
Cropping system					
Summer grain/winter cover–main	6.9	1.9	8.9	9.2	18.0
Summer grain/winter cover–alternative	10.2	4.0	14.2	10.8	25.0
Winter grain/summer cover–main	4.7	0.2	4.9	0.3	5.2
Winter grain/summer cover–alternative	5.4	1.0	6.4	3.0	9.4
LSD _(0.05)	1.9	2.9	3.6	5.2	6.9
Tillage regime					
Conventional tillage	8.0	3.2	11.2	8.5	19.7
No tillage	5.7	0.4	6.0	3.2	9.2
LSD _(0.05)	1.8	2.4	3.2	4.6	6.2
Cover crop management					
Ungrazed	6.1	1.5	7.6	6.9	14.5
Grazed	7.5	2.1	9.6	4.8	14.3
LSD _(0.05)	1.8	2.5	3.2	4.6	6.2

within the 0–150-cm profile of a Typic Argiudoll in Nebraska (Kessavalou and Walters, 1999), and $457 \pm 176 \text{ kg N ha}^{-1}$ within the 0–210-cm profile of Udic Argiustoll/Udertic Paleustoll in Oklahoma (Raun and Johnson, 1995).

Rate of change in soil nitrate-N content varied significantly by cropping system and tillage regime, and to a much lesser extent cover crop management (Table 3). Rate of change in soil nitrate-N content was greater in the summer grain/winter cover crop system than the winter grain/summer cover crop system at all depths – the difference averaging $3.5 \text{ kg ha}^{-1} \text{ year}^{-1}$ in the upper rooting zone ($P < 0.001$), $2.4 \text{ kg ha}^{-1} \text{ year}^{-1}$ in the lower rooting zone ($P = 0.03$), and $8.4 \text{ kg ha}^{-1} \text{ year}^{-1}$ in the zone typically below rooting ($P < 0.001$). Replacement of unfertilized leguminous cover crops with fertilized grass cover crops during the last couple of years had an effect on soil nitrate-N content primarily in the upper rooting zone, where the rate was greater by an average of $2.0 \text{ kg ha}^{-1} \text{ year}^{-1}$ ($P = 0.007$). Curiously, the rate of change in soil nitrate-N was either not related or even negatively related to the N excess of a cropping system. There was, however, a strong correlation between mean N input ($\text{kg N ha}^{-1} \text{ year}^{-1}$) and rate of nitrate-N accumulation at all soil depths ($r^2 = 0.90 \pm 0.04$). At least in the relatively short time period of this evaluation and in systems receiving relatively low N inputs in all cases, the rate of N fertilizer input appeared to be more important in controlling the rate of soil nitrate-N accumulation than the N output from harvested grain. These relationships regarding N input and soil nitrate-N accumulation agreed with those observed in a 5-year pasture study at a nearby location, but the strong difference between fully harvested hayland and unharvested conservation land provided the necessary N sink strength to make N output a key factor in controlling soil nitrate-N dynamics (Franzluebbers and Stuedemann, 2003).

Disturbance of surface soil with conventional disk tillage as compared with no disturbance was expected to mineralize N from organic matter and provide a greater source of inorganic N. Our results were in support of this hypothesis, as there was significantly lower soil nitrate-N content accumulation under NT than under CT at all soil depths during the course of this study. These results confirm several reports of lower soil nitrate-N content at various locations in the soil profile under NT compared with CT (Angle et al., 1993; Dou et al., 1995; Kessavalou and Walters, 1999).

Lack of difference in soil nitrate-N accumulation between ungrazed and grazed cover crop management was contrary to our

hypothesis that grazing of cover crops would stimulate a faster breakdown of plant residues and lead to greater inorganic N accumulation. The literature is scant on the topic of grazing-induced changes in soil nitrate-N content. In a 5-year pasture study at a nearby location, soil nitrate-N accumulated in the rooting zone at a rate of $5 \pm 3 \text{ kg N ha}^{-1} \text{ year}^{-1}$ under both low grazing pressure and unharvested conservation management, but accumulated at $9 \pm 4 \text{ kg N ha}^{-1} \text{ year}^{-1}$ under high grazing pressure (Franzluebbers and Stuedemann, 2003).

4. Conclusions

Accumulation of soil nitrate-N occurred in all management strategies following conversion of perennial pasture on this Typic Kanhapludult to an integrated crop-livestock system. Whole-profile nitrate-N content (0–150-cm depth) averaged 149 kg N ha^{-1} (equivalent of $7 \text{ mg NO}_3\text{-N kg}^{-1}$), overall a moderate level. Strategies found to minimize nitrate-N accumulation in the zone typically below rooting (90–150-cm depth) were no-tillage and cropping systems with reduced N fertilizer inputs. The impact of cattle grazing cover crops was variable – significantly greater soil nitrate-N content with than without grazing occurred below the rooting zone at the end of 3 and 4 years only, while lower soil nitrate-N content with than without grazing occurred in the rooting zone at the end of 6 year. Regression analysis with time indicated no effect of grazing on soil nitrate-N content. This study illustrated that diverse cropping systems using integrated crop-livestock approaches can be developed to achieve both production and environmental quality objectives, although N management for high crop production and avoidance of negative environmental consequences requires continual evaluation of N inputs, N outputs, and ecosystem responses.

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